Hyperloop Onboard Unit Operations Analysis*

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Group 7

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2 Abstract

The following technical report evaluates and analyzes the onboard compressor and propulsion of Elon Musk's Hyperloop system, a proposed alternative method of transit for the California high-speed bullet train. After calculating and verifying the detailed schematic from Tesla Motor's website, the following recommendations and suggestions for improvement are included. After creating a Pugh Matrix and evaluating alternative components to the design, the most viable and feasible energy unit operations that should be utilized in the Hyperloop are the axial compressor, nozzle expander (de Laval), and a plate heat exchanger (intercooler). They provide advantages in cost, size, efficiency, capacity, and environmental, health and safety.

3 Introduction

In order for the Hyperloop to be a viable mode of transportation, the design of its mechanics must be feasible. However, there are currently no prototypes of the Hyperloop, which makes it an unreliable technology. Thus, the main goal of this project is to prove, or disprove, the feasibility of the Hyperloop technology.

The Hyperloop contains capsules, which will carry an average of 28 passengers. The capsules are supported via air bearings that operate using a compressed air reservoir and aerodynamic lift. (1) A main compressor provides thrust to propel the passenger capsule and also reduces air drag. A second compressor is used for the air bearings to support the weight of the capsule throughout the trip.

The team faces three essential goals. First, analyze the design presented by Musk for the passenger capsule to verify its feasibility. Second, estimate the drag force of the air between the capsule and the tube and compare it to Musk's predictions. Lastly, suggest improvements to the current onboard compressor system or recommend a new design to that shown below from the Hyperloop document article (Figure 1).

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4 Analysis of Elon Musk's Design

Original Design Schematic

Musk provides a schematic for the compressor used on the Hyperloop as seen below (Figure 1). His design includes two compressors, three reservoirs (for water, steam, and air), two intercoolers/heat exchangers to cool the air, and an expander in order to produce thrust out of the compressor. When performing calculations on each of the unit operators for our evaluation, we use the values presented in the schematic.

Assumptions

The following assumptions are made in the Hyperloop analysis. First, it is assumed that the air follows ideal gas behavior and it flows at steady state. Second, both axial compressors are assumed to be adiabatic. Finally, both intercoolers are assumed to be isobaric. (Most intercoolers used today are nearly isobaric in order to have as much air charge density as possible.)

Discussion of Calculations

The following section discusses the calculations used to verify the Hyperloop schematic. The calculations can be found in Appendix I.

Part I: Verifying Feasibility of Hyperloop

Efficiency

Finding the efficiency of the on board compressor is the primary focus of our calculations. The processes for calculating the efficiency of both axial compressors are essentially identical. Using the values already given in the Hyperloop schematic (pressure, volume, mass, and power), we combine an energy and entropy balance to find isentropic work. In order to calculate isentropic work, we must find the Cp constant of the system, which was calculated to be 0.814 kJ/kg/K. Using this value and the fact that efficiency is the ratio between isentropic work versus actual work, we are able to calculate the efficiencies of both compressors. The efficiency of the first axial compressor is 81.67%, while the efficiency of the second compressor is 75.92%.

Size of Heat Exchanger

Unit operation sizes are also important to the feasibility of the design. The volume occupied by the heat exchanger units on board were extrapolated from the power required in order to operate the exchangers. The heat exchangers in the Hyperloop design use an on board reservoir of coolant (water) to lower the temperature of the air displaced by the capsule through the compressor. From our calculations, this intercooler must take in 0.14 kg/s of coolant, so throughout the duration of each trip, approximately 290 kg of water and steam must travel through the exchanger, which requires a power of approximately 288.2 kW. Based off of this value, the team was able to find a real world, vehicular analog and calculated a required heat exchanger size of 0.0016 m^3.

Size of Nozzle

We are able to find the capacity the nozzle requires by estimating based on the cross- sectional area of the capsule. Because the width and the height of the capsule are 1.35 m and 1.86 m respectively, we know that the nozzle cannot exceed of this space. Instead, we assume that the area of the nozzle output is approximately half of the capsule rear, which is a reasonable assumption for providing thrust. From here, we assume that the nozzle expands for from 0.5 m to 1.0 m, allowing us to determine that a feasible nozzle volume must fall between 0.314 m^3 to 0.6277 m^3.

Mass of Capsule

Although the mass of the capsule is important for our Hyperloop analysis, with the limited amount of information provided by Musk's document, we are unable to obtain a quantitative solutionestimate. For example, Musk never does not specifyies the length of the capsule because he himself is unsure how many people he plans to fit inside one capsule. He also never mentions any the specific companies he plans to purchase compressors, nozzles, or even heat exchangers from. Without this information, we cannot fully quantify the exact weight of each capsule.

Part II: Estimating Capsule Drag

Capsule Drag
In the Hyperloop document, the drag force is given as 320 N.1 The team verifies this value using the complete drag force equation. First, we calculate a Reynolds Number of 45,479, indicating a turbulent flow. Using a drag coefficient of 0.005 and assuming that the front of the Hyperloop projects as a flat plate at turbulent flow, a drag force of 0.820 N is calculated. This value corresponds to the drag force due to friction and is negligible in regards to the overall drag force. This result supports the concept that at high Reynolds numbers, the drag found is predominantly due to pressure. (2) Thus, almost all the drag force produced must be due to the pressure gradient in the system. Using the 320 N drag force given by Musk, the pressure gradient is calculated as a change from 99 Pa to 556 Pa. This change is a very reasonable pressure gradient and is much less than a gradient of 101325 Pa (atmospheric pressure). Thus, it is concluded that the given drag force value of 320 N is reasonable.
Volume of Air Taken in by Onboard Compressor/Air Displaced
For the Hyperloop to function properly, the maximum volume of air that can be taken in by the onboard compressor must be greater than or equal to the volume displaced. (1) Assuming that the air behaves as an ideal gas and using the given air flow rate of 0.49 kg/s, the volumetric flow rate of air is calculated to be 414.67 m3/s, which is the volume of air displaced per second. Using this value, we calculated that a total volume of 870746,807406 m3 is displaced for the entire duration of the 350-minute ride. During the ride, the compressor can take in no more than 40% of the total air at any given time. The volumetric flow rate of 414.67 m3/s of air and the volume of air flowing around the capsule (870,807 m3) meets these qualifications.

5 Recommendations and Suggested Improvements

Consideration of Alternative Design
To ensure the most effective Hyperloop design, the team evaluated different options for the three main unit operations (compressor, expander, and intercooler) used in the Hyperloop system against five design criteria: cost, efficiency, capacity, size, and Environmental, Health, and Safety (EHS).
Introduction to Analyzed Unit Operations

Compressor
Compressors are used for an increase in pressure to bring fluids to the proper pressure for either reacting or processing. This pressure increase can be accomplished with rotating blades or in cylinders with reciprocating pistons. (3) For the Hyperloop system, four different compressors are analyzed: reciprocating, rotary, centrifugal, and axial. Centrifugal compressors rotate their blades around a center point, taking advantage of centrifugal force. Unlike centrifugal compressors, axial compressors let the fluid flow parallel to the axis of rotation without a radial component. Reciprocating compressors use pistons in cylinders to drive the fluid. Rotary compressors use a rotary screw in a continuous sweeping motion and are practical for high-pressure systems. (4)
Expander
Three different expanders are analyzed: converging diverging (CD) nozzles, turbines (Figure 2), and rocket engines. In a CD nozzle (Figure 3), gas flows through a region of high-pressure to one of low-pressure. The gas converges to the throat of the nozzle and goes through the diverging area and "then exhausts into the ambient as a jet". (5)

A turbine consists of alternate sets of nozzles and rotating blades where gas flows in an expansion process. The internal energy of high pressure and temperature gas is converted to mechanical work through rotating output shafts. (3) A rocket engine consists of a compression device, a combustion chamber, as well as a nozzle. The kinetic energy of the exhaust gases is directly available for propelling the engine. (3) For rocket engines, the oxidizing agent and fuel are carried inside the engine.
Heat Exchanger
Heat exchangers are used to transfer energy from one fluid to another.

Three additional different types of heat exchangers are considered as potential replacements for the proposed air-to-liquid intercooler (ATLI) in the Hyperloop design: double-pipe heat exchangers (DPHE),

shell-and-tube heat exchangers (STHE), and plate heat exchangers (PHE).

In a DPHE (Figure 4), two fluids flow in a concentric tube construction: a hot fluid flows in a central pipe, while a cool fluid flows in a pipe that encapsulates the central pipe. (6)

In a STHE (Figure 5), a fluid flows in a series of tubes, while the other fluid flows along an outer shell that runs parallel to the tubes. (7)

In a PHE (Figure 6), a series of corrugated plates are held in contact with each other. Two fluids simultaneously flow separately across neighboring channels in the corrugation channels. (7)

The final design evaluated is the ATLI (Figure 7), which is the heat exchanger currently proposed in Musk's schematic. An ATLI removes heat from air and stores this heat in a liquid (generally water). (8)

Definition of Criteria

In our analysis, five criteria are used to evaluate each unit operation: cost, efficiency, size, capacity, and EHS.

Cost, Efficiency, and Size

The definitions of cost, efficiency, and size are the same for each unit operation. Cost, deemed the most important criterion for unit operation evaluation, includes the initial cost of purchasing the unit operation, as well as the operating costs associated with the device. The initial and operating costs are considered equally in this evaluation. Efficiency is defined as the amount of available power the system can produce (generally under isentropic conditions) compared to how much power is put into the system. The size of a unit operation is defined as the amount of space it takes up within its allotted space in the Hyperloop capsule. Size can be evaluated in terms of both volume and weight. Ideally, a smaller, lighter unit operation is preferable for the Hyperloop.

Capacity and EHS

The definitions of the remaining two criteria, capacity and EHS, differ based on unit operations due to the nature and construction of each device.

Capacity

Compressor capacity is defined in terms of pressure range (pounds per square inches gauge) and capacity range (actual cubic feet per minute). The values for these ranges are shown in Figure 8. Because the Hyperloop operates at near atmospheric pressure, a low-pressure range is desired.

The factors the team accounts for when analyzing the capacity of expanders are the thrust force and the feasibility. The amount of thrust force an expander can provide is essential to the movement of the capsule. If a device cannot provide enough thrust, the air drag between the capsule and tube wall will inhibit the movement of the Hyperloop. The size and cost of expanders can prevent them from being a viable option in the design of the Hyperloop.

In the analysis of the heat exchanger unit operation, capacity is divided into two subcategories: temperature and pressure. The temperature and pressure capacities are defined as the maximum temperature and pressure, respectively, at which the heat exchanger can operate under normal conditions.

EHS

In the EHS criterion for compressors, the team must consider maintenance, noise, and safety. Maintenance is the time and effort required for repairing the compressors and keeping them in good operating conditions. This component depends on the amount of parts in each compressor, as well as how frequently maintenance checks and repairs must be conducted. Additionally, noise is also an important consideration in regards to the passenger's level of comfort, because some compressors are louder than others. Finally, the last consideration is passenger safety. The safety concerns that come with compressors are only present for those working with the equipment and will not be relevant to the passengers. (4)

In the analysis of the EHS factors for expanders, maintenance, noise, and safety are considered. Maintenance is an important factor because expanders can have multiple parts, such as diffusers and combustion chambers. With a more complex system, there is a higher chance of having to replace a part. Additionally, noise is considered for EHS due to the sound of high-pressured fluids running through the expanders. Finally, when considering the safety of expanders, factors such as pressure and the flow of fluids in and out of the machines must be evaluated.

In the analysis of the heat exchanger unit, the EHS criterion is divided into two subcategories: maintenance and safety. Maintenance involves the amount of time and manpower that is necessary to clean and maintain the heat exchanger. Maintenance also accounts for any routine servicing that needs to be done in order to keep the heat exchangers operating normally. The safety subcomponent accounts for any hazards associated with the particular type of heat exchanger. Some hazards include potential for leakage, non-uninsulated areas, or flow-induced vibrational issues. Noise is not addressed in the heat exchanger analysis because the different types of heat exchangers evaluated operated at comparable noise levels..

6 Pugh Matrix

			Compressors			
			Recipricating	Rotary	Centrifugal	Axial
Cost		30.00%	3.00	4.00	4.00	5.00
Efficiency		25.00%	5.00	2.00	2.00	5.00
Capacity		25.00%				
	Pressure		5.00	2.00	4.00	3.00
Size		10.00%	1.00	5.00	5.00	4.00
EHS		10.00%	2.67	4.33	3.33	5.00
	Maintenance		2.00	4.00	1.00	5.00
	Noise		1.00	4.00	4.00	5.00
	Safety		5.00	5.00	5.00	5.00
Total		100.00%	3.77	3.13	3.53	4.40

			Expanders		
			Nozzle (de Laval)	Turbine	Rocket Engine
Cost		30.00%	4.00	2.00	1.00
Efficiency		25.00%	5.00	1.00	3.00
Capacity		25.00%	3.50	2.50	3.00
	Thrust Force		3.00	2.00	5.00
	Feasibility		4.00	3.00	1.00
Size		10.00%	5.00	3.00	1.00
EHS		10.00%	3.67	2.00	1.00
	Maintenance		4.00	2.00	1.00
	Noise		3.00	2.00	1.00
	Safety		4.00	2.00	1.00
Total		100.00%	4.19	1.98	2.00

			Heat Exchangers			
			Double Pipe	Shell & Tube	Plate	Air-to-Liquid
Cost		30.00%	4.00	3.00	5.00	4.00
Efficiency		25.00%	3.00	2.00	4.00	5.00
Capacity		25.00%	4.00	5.00	3.00	3.00
	Temperature		4.00	5.00	3.00	3.00
	Pressure		4.00	5.00	3.00	3.00
Size		10.00%	2.00	3.00	5.00	4.00
EHS		10.00%	4.00	4.00	4.00	4.00
	Maintenance		4.00	5.00	4.00	4.00
	Safety		4.00	3.00	4.00	4.00
Total		100.00%	3.75	3.65	4.65	4.40

Justification of Weighting

On our Pugh Matrix, cost has the greatest weight at 30%. Cost is ranked highest because it is deemed the most important feature of the unit. For example, if a unit is too expensive to be financially feasible, it will not be a viable option of the Hyperloop regardless of other features.

Efficiency and capacity are given the second highest rankings and are each weighted 25%. Efficiency is very important in evaluating the unit to be used on the system. In order for a unit to be practical, it

must operate at a high efficiency so that it can function without great difficulty. In addition, the capacity is important as well. Each of the units can only operate under specific parameters, and if the unit does not have a sufficient capacity it will not be a suitable choice because it cannot operate under the Hyperloop requirements. SinceBecause capacity is divided into two subgroups that vary based on the unit operation (see "Definition of Criteria"), each subgroup was given a weighting of 12.5%.

The last two characteristics used for ranking are size and EHS, and each areis ranked 10%. The size is important to the Hyperloop because the unit must fit within a predefined space. However, for most units, size was comparable between the different types. Thus, it is only ranked 10%. The EHS subgroups described above ("Definition of Criteria") are given equal rankings such that their total is 10%. EHS is only ranked at 10% because most of the units are relatively safe and do not have an extremely high level of maintenance within the environment they will be implemented. However, some units are an exception to this rule and received a low score on the Pugh matrix.

Analysis of Unit Operations

Compressor

The axial compressor is the most suitable compressor to use in the Hyperloop. In terms of cost, axial, centrifugal, and rotary compressors all receive high scores of 4 or 5. Axial receives the highest score due to its continually low operating cost.

In terms of efficiency, both reciprocating and axial compressors achieve scores of 5 for their high efficiency ratings. Rotary and centrifugal compressors both have efficiencies under 60% and thus receive lower scores of 2.

Moreover, for capacity and pressure, reciprocating compressors have the highest range and meet the pressure requirement for the Hyperloop system. Furthermore, the sizes of the rotary and centrifugal compressors are compact, so they each receive a score of 5.

Finally, in terms of the EHS criterion, all the compressors receive a score of 5 for safety because they each have similar safety concerns. When evaluating noise, only the reciprocating compressor scores low due to its loud operating sounds. For maintenance, the axial compressor receives a 5. The only concern with axial compressors emerges from airborne contaminant particles, which are not a concern in the Hyperloop system.

Overall, the axial compressor has the highest score with a Pugh matrix rating of 4.40.

Expander

Out of all three expanders, the nozzle is the most suitable expander to implement in the design of the Hyperloop. Due to the multi-component system of the rocket engine, the cost is not practical to run a system of passenger capsules.

Additionally, the efficiency of turbines runs lower than 50%, which is impractical compared to the 90% efficiency achieved in nozzles. In addition, the thrust force of a turbine is not enough to propel the capsule through the tube while resisting air drag from the sides. Although rocket engines can provide more than enough thrust force, the volume that it occupies makes it an unreasonable option.

Moreover, the nozzle excels in the EHS criterion. It requires minimal maintenance because it is a simple device that does not require fuel or constant attention. Also, because the pressures going in and out of the nozzle rise just above and below the atmospheric pressure, the noise will not be an issue. Furthermore, when evaluating safety, the nozzle proves to be the most reliable. It does not require any combustion chambers, nor does it handle steam at high temperatures and pressures. For the reasons explained above, the nozzle is the chosen device for the expander in the design of the Hyperloop with an overall Pugh matrix score of 4.19.

Heat Exchanger

The plate heat exchanger received the highest score (4.65) in the Pugh matrix evaluation. The PHE has the lowest initial purchasing cost of the four heat exchangers and is generally regarded among the most economical of heat exchangers, so it receives a rating of 5. (9) The other heat exchanger options receive lower scores because of high capital or operating costs. For example, the STHE receives a lower ranking of 3 because its construction can be heavy and intensive, increasing initial production costs. (19)

In terms of efficiency, the PHE ranks second out of the four heat exchangers, due to its overall high heat transfer coefficient, resulting in a greater efficiency than shell and tube exchangers and a score of 4. (20)

However, when evaluating heat exchanger capacity, the PHE ranked averagely compared to the other three heat exchangers with a score of 3, with a maximum operating pressure of only 145 psi and a maximum temperature operating range of 150 - 400 °C. (16,21,9,22) However, these temperature and pressure ranges are within the Hyperloop operating range, so there is no cause for concern when using the PHE.

Additionally, the PHE's size is ideal because it can be implemented at a wider range of sizes (1-2500 m^2), resulting in a score of 5. While the ATLI is compact, it cannot operate under as long of a range of sizes as the plate heat exchanger. Both the STHE and the DPE receive lower rankings, either because they are larger or because they require multiple units to operate.

Lastly, in terms of EHS, the PHE is not as low-maintenance as the STHE; however, it still receives a ranking of 4 because requires relatively low-maintenance to operate. Additionally, the PHE ranks among the highest for the other EHS subcategory, safety. Unlike the STHE and the DPE, which can be subject to flow-induced vibration that are hazardous to onboard equipment, the main problem associated with PHEs is potential leakage. (9,19,6) Because leakage can be fixed more easily than flow-induced vibrations, the PHE ranks highly in safety.

Due to its advantages in size, cost, safety, and efficiency, the PHE is the ideal choice for the heat exchanger unit operation.

In conclusion, the ideal combination of unit operations the team suggests for implementation in the Hyperloop system consists of the axial compressor, the nozzle expander, and the plate heat exchanger. Both the axial compressor and nozzle expander are already used in Musk's design; however, the plate heat exchanger is recommended over Musk's suggested ATLI due to its slightly lower initial and operating costs.

Limitations of Analysis

The limitations of analysis are previously addressed in the report. For reiteration, the calculations are based off of very idealized conditions. It would be very different in reality to apply the applications without considerable testing and modifications.

Additional Recommendations

In addition to the new unit operations combination suggested, the team also considered changing the power sources used in the existing Hyperloop design to improve the technology.

For powering the rail gun that accelerates the Hyperloop pods, the team recommends using LightSail technology. The rail gun requires a large amount power of over for a short period of time to accelerate the Hyperloop capsules, and LightSail can meet this time restriction. Additionally, there is plenty of space on the exterior of the tube for the implementation of the LightSail power system. Moreover, using LightSail to accelerate the pods will not put any additional load on the vacuum pumps, rendering the design effective. Furthermore, Danielle Fong, creator of LightSail, endorses the use of LightSail technology for this proposed purpose. (23)

Furthermore, Musk's Hyperloop Alpha report limits itself to solar panels as its primary method of power generation. While solar panels are a form of renewable and sustainable energy, there are many other potential sources of energy that should be taken into consideration. Production of natural gas, for example, has recently reached an all time high in the United States. This new abundance of domestic resource should be taken into consideration. Not only are natural gas prices per kWh half of those of solar panels ($0.057/kWh), but this fuel also emits 40% less carbon emissions compared to its other carbon fuel analogs such as coal or gasoline. (25) Understandably, utilization of natural gas is nowhere near as aesthetically pleasing as solar panels, but from an economic standpoint, it would be unwise to completely disregard natural gas as a potential power source for the Hyperloop Alpha. From Musk's report, the Hyperloop is projected to require an average of 21MW of energy annually. With natural gas prices at such low prices, it would only cost approximately $1,200 to power the Hyperloop for one year with natural gas while the startup capital for solar panels is upwards of $210 million dollars.

Geothermal energy is another force to consider when choosing between methods of power generation. There is currently nothing about the Hyperloop design that prevents it from utilizing geothermal energy as its primary source of power. In fact, the largest group of geothermal power plants is located just above San

Francisco, perfect for providing the Hyperloop with the energy it needs. (26) With low costs comparable to those of natural gas, geothermal energy is another clean alternative that is highly untapped in Musk's report. Because geothermal energy in California is even cheaper than natural gas, the economics for this power source are uncontestable. There are, however, issues with energy transport from northern San Francisco to Los Angeles.

7 Conclusion

Elon Musk's proposed Hyperloop system schematic is deemed effective due to the high compressor efficiencies and reasonable unit operation sizes. In addition, the drag force proposed by Musk is also plausible, especially in terms of the pressure gradient experienced during Hyperloop operation. However, in an effort to improve the Hyperloop's design, the team performed further analysis of the unit operations used in the Hyperloop system.

After careful evaluation against the selected design criteria, the ideal sequence of unit operations for a feasible Hyperloop design is the axial compressor, the nozzle expander-plate, and the plate heat exchanger combination. These three unit operations each received the highest score in their respective Pugh matrices, making them the ideal choice for the Hyperloop system.

Lastly, the team analyzed several potential changes to the Hyperloop's power system. These possible recommended changes to the Hyperloop include using LightSail technology to power the accelerator, considering natural gas as a potential method of power generation, and using geothermal power as a clean energy alternative to power the system.

Overall, while the Hyperloop already exhibits many advantageous qualities and characteristics, by improving the type of intercooler used and exploring alternative power sources, the design could emerge as a frontrunner for an alternative method of transportation technologies.

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9 Appendix

Appendix I

APPENDIX I – Calculations

Overall Assumptions

- Ideal gas behavior
- Fully developed flow → steady state

Part I - Axial Compressor #1

P_{in} = 99 Pa = .099 kPa

T_{in} = 292 K

m_{in} = 0.49 kg/s

W_c = 276 kW

P_{out} = 2.1 kPa

T_{out} = 857 K

Assumptions

- Adiabatic Q = 0
- Ideal gas behavior
- R = 8.314 L*kPa/(K*mol)

Energy balance:

$$\frac{d(mU)}{dt} = -\Delta\left[\left(H + \frac{u^2}{2} + g \cdot z\right) \cdot m\right] + Q + W$$

$$(H_{out} - H_{in}) \cdot m = W_s$$

Entropy balance:

$$\frac{d(mS)}{dt} + \Delta(m \cdot S) - \frac{Q}{T_\sigma} = SG \geq 0$$

$$m \cdot (S_{out} - S_{in}) = S_G \geq 0$$

$$dS = Cp\frac{dT}{T} - \frac{V}{T}dP = 0$$

$$C_p \cdot \ln\left(\frac{T_2}{T_1}\right) = R \cdot \ln\left(\frac{P_2}{P_1}\right)$$

$$C_p \cdot \ln\left(\frac{857}{292}\right) = (8.314) \cdot \ln\left(\frac{2.1}{.099}\right)$$

$$C_p = 23.587\ \frac{J}{mol \cdot K}$$

$$\left[\frac{23.587\ J}{mol \cdot K}\right] \cdot \left[\frac{1\ mol}{28.97\ g}\right] \cdot \left[\frac{1000\ g}{1\ kg}\right] \cdot \left[\frac{1\ kJ}{1000\ J}\right] = C_p = 0.814\ \frac{kJ}{kg \cdot K}$$

$$W_s^{isentropic} = m \cdot C_p \cdot \Delta T$$

$$W_s^{isentropic} = \left(0.49\ \frac{kg}{s}\right) \cdot \left(0.814\ \frac{kJ}{kg \cdot K}\right) \cdot (857\ K - 292\ K)$$

$$W_s^{isentropic} = 225.407\ \frac{kJ}{s} = 225.407\ kW$$

$$\eta = \frac{W_s^{isentropic}}{W_s} = \frac{225.407\ kW}{276\ kW} = 0.8167 \rightarrow 81.67\%$$

Part II - Intercooler #1

Stream 1 – air in

P_1^{in} = 2.1 kPa

T_1^{in} = 857 K

m_1^{in} = 0.49 kg/s

stream 2 – water in

P_2^{in} = 101 kPa

T_2^{in} = 293 K

m_2^{in} = 0.14 kg/s

stream 3 – air out

P_3^{in} = 2.1 kPa

T_3^{in} = 300 K

m_3^{in} = 0.49 kg/s

stream 4 – steam out

Assumptions

- Isobaric

Energy Balance:

$$\frac{d(mU)}{dt} = -\Delta\left[\left(H + \frac{u^2}{2} + g \cdot z\right) \cdot m\right] + Q + W$$

$$(H_{out} - H_{in}) \cdot m = 0$$

$$H_{out} \cdot m = H_{in} \cdot m$$

$$H_3 \cdot m_3 + H_4 \cdot m_4 = H_1 \cdot m_1 + H_2 \cdot m_2$$

$H_4 = 888\ \frac{kJ}{kg}$ (steam tables)

Part III - Split point

Stream 1 – stream in

H_1^{in} = 300.2 kJ/kg

T_1^{in} = 300 K

m_1^{in} = 0.49 kg/s

stream 2 – stream out

T_2^{in} = 300 K

m_2^{in} = 0.29 kg/s

stream 3 – stream out

T_3^{in} = 300 K

m_3^{in} = 0.2 kg/s

Part IV - Intercooler #2

Stream 1 – air in

P_1^{in} = 11 kPa

T_1^{in} = 557 K

m_1^{in} = 0.2 kg/s

stream 2 – steam in

P_2^{in} = 101 kPa

T_2^{in} = 293 K

m_2^{in} = 0.14 kg/s

stream 3 – air out

P_3^{in} = 11 kPa

T_3^{in} = 400 K

m_3^{in} = 0.2 kg/s

stream 4 – steam out

Assumptions

- Isobaric

Energy Balance:

$$\frac{d(mU)}{dt} = -\Delta\left[\left(H + \frac{u^2}{2} + g\right.\right.$$

$$(H_{out} - H_{in}) \cdot m = 0$$

$$H_{out} \cdot m = H_{in} \cdot m$$

$$H_3 \cdot m_3 + H_4 \cdot m_4 = H_1 \cdot m$$

$H_4 = 565\ \frac{kJ}{kg}$ (sta

Part V - Nozzle Expand

H_1^{in} = 300.2 kJ/kg

T_1^{in} = 300 K

m_1^{in} = 0.29 kg/s

W_s = -58 kW

F_{thrust} = 170N

P_{thrust} = 58 kW

Energy Balance:

$$\frac{d(mU)}{dt} = -\Delta\left[\left(H + \frac{u^2}{2} + g\right.\right.$$

$$(H_{out} - H_{in}) \cdot m = -W_s$$

$$H_{out} = -\frac{W_s}{m} + H_{in}$$

$$H_{out} = -\frac{58\ kW}{0.29\ \frac{kg}{s}} + 300.2\frac{kJ}{kg}$$

$$H_{out} = 100.2\frac{kJ}{kg}$$

$$\Delta H = C_p \cdot \Delta T$$

$$Cp = 1.047\ \frac{kJ}{kg \cdot K}$$

$$H_{out} - H_{in} = C_p \cdot (T_{out} - T_{in})$$

T_{out} = 108.97 K

Entropy Balance:

$$\frac{d(mS)}{dt} + \Delta(m \cdot S) - \frac{Q}{T_\sigma} = SG$$

$$m \cdot (S_{out} - S_{in}) = S_G \geq 0$$

Isentropic S_{in} = S_{out}

$$dS = Cp\frac{dT}{T} - \frac{V}{T}dP = 0$$

$$C_p \cdot \ln\left(\frac{T_2}{T_1}\right) = R \cdot \ln\left(\frac{P_2}{P_1}\right)$$

Part VI - Axial Compressor #2

P_{in} = 2.1 kPa

T_{in} = 300 K

m_{in} = 0.2 kg/s

W_s = 52 kW

P_{out} = 11 kPa

T_{out} = 557 K

Energy Balance:

$$\frac{d(mU)}{dt} = -\Delta\left[\left(H + \frac{u^2}{2} + g * z\right) * m\right] + Q + W$$

$$(H_{out} - H_{in}) * m = W_s$$

Entropy Balance:

$$\frac{d(mS)}{dt} + \Delta(m * S) - \frac{Q}{T_\sigma} = SG \geq 0$$

$$m * (S_{out} - S_{in}) = S_G \geq 0$$

$$dS = Cp\frac{dT}{T} - \frac{V}{T}dP = 0$$

$$C_p * \ln\left(\frac{T_2}{T_1}\right) = R * \ln\left(\frac{P_2}{P_1}\right)$$

$$C_p * \ln\left(\frac{557}{300}\right) = (8.314) * \ln\left(\frac{11}{2.1}\right)$$

$$C_p = 22.250\frac{J}{mol * K}$$

$$\left[\frac{22.250\ J}{mol * K}\right] * \left[\frac{1\ mol}{28.97\ g}\right] * \left[\frac{1000\ g}{1\ kg}\right] * \left[\frac{1\ kJ}{1000\ J}\right] = C_p = 0.768\frac{kJ}{kg * K}$$

$$W_s^{isentropic} = m * C_p * \Delta T$$

$$W_s^{isentropic} = \left(0.2\frac{kg}{s}\right) * \left(0.768\frac{kJ}{kg * K}\right) * (557\ K - 300\ K)$$

$$W_s^{isentropic} = 39.476\frac{kJ}{s} = 39.476\ kW$$

$$\eta = \frac{W_s^{isentropic}}{W_s} = \frac{39.476\ kW}{52\ kW} = 0.7592 \rightarrow 75.92\%$$

Image not finished

Part VII - Friction of capsule

Givens

D = 2.23 m

A_p = 1.4 m²

T = 293.15 K

P = 100 Pa

F_d = 320 N

μ = 1.83e-5 Pa*s = 1.83e-2 g/(m*s)

Reynolds Number

Re = D_p*v_*ρ/μ

$$Re = \frac{(2.23m)\left(313.89\frac{m}{s}\right)\left(1.189\frac{g}{m^3}\right)}{1.83e-2\frac{g}{m*s}} = 45{,}479$$

$$> 2100\ turbulent$$

Drag Force

$$F_d = c_p * \frac{v_\infty^2}{2} * \rho * A_p$$

$$v_\infty = 1130\frac{km}{hr} * \frac{1\ hr}{3600\ s} * \frac{1000\ m}{1\ km} = 313.89\frac{m}{s}$$

Cd for streamlined object, unidirectional flow, turbulent

$$C_d = \frac{2F_d}{\rho v^2 A} = c_p + c_f$$

$$C_d = \frac{1}{\rho v^2 * A}\int(p - p_0).n.i dA + \frac{1}{\rho v^2 * A}\int T_w.t.i dA$$

$$C_d = \frac{0.0576}{Re^{0.25}} = \frac{0.0576}{(45{,}479)^{0.25}} = 0.006743$$

$$C_p = \frac{1}{\rho v^2 * A} * (P - P_0) * A = \frac{1}{\rho * v^2} * (P - P_0)$$

$$C_p = \frac{1}{\left(1.189e-3\frac{kg}{m^3}\right) * \left(313.89\frac{m}{s}\right)^2} * (P - 99\ Pa)$$

$$\frac{2 * 320\ N}{\left(1.189e-3\frac{kg}{m^3}\right) * \left(313.89\frac{m}{s}\right)^2 * (1.4\ m^2)} = 0.00854\frac{m s^2}{kg} * \frac{(P-99) kg}{m s^2}$$

$$\frac{640\ kg * \frac{m}{s^2}}{164.01\ kg * \frac{m}{s^2}} = 0.00854 * (P - 99)$$

P = 555.94 Pa

Ideal gas behavior

$$\frac{\rho}{MW} = \frac{n}{V} = \frac{P}{RT}$$

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Appendix II

APPENDIX II – Pugh Matrix

Qualitative Analysis

			Compressors			
			Reciprocating	Rotary	Centrifugal	Axial
Cost		30.00%	more than centrifugal	low	low	low operating cost
Efficiency		25.00%	high	poor <60%	poor <60%	high
Capacity		25.00%	low → high	low → medium	medium → low	low → high
	Pressure		medium-very high	low-medium	medium-high	
Size		10.00%	large	compact	compact	varies
EHS		10.00%				
	Maintenance		many parts	few parts	sensitive to air	comes from airborne contaminant particles
	Noise		high	low	low	audible if next to it
	Safety		safe	safe	safe	safe
Total		100.00%				

			Expanders		
			Nozzle (de Laval)	Turbine	Rocket Engine
Cost		30.00%	varies depending on size used	the smaller, the more expensive	high, costs from nozzle & turbine
Efficiency		25.00%	high, about 95%	the smaller, the less eff. <40%	turbine < rocket, engine < expander
Capacity		25.00%		500kW to 150MW (too big)	irrelevant, no P differential
	Thrust Force		exit air can be subsonic/supersonic	high pressure capacity	huge thrust force
	Feasibility		numerous nozzles used for gas expanders		not at all
Size		10.00%	various sizes	large	huge
EHS		10.00%	no harm to environment	very clean	bad, contaminants, CO and CO2
	Maintenance		orifice can be damaged after high P gas	25-50,000 hrs life and a few parts	refueling of both liquids & ox. agent
	Noise		depends on speed of gas inlet	exceeding sound speed, silencers avail.	very loud, combustion of fuels
	Safety		hot gases flow in, high vel gas exit	multiple parts that must be air tight	hazardous gases in closed container
Total		100.00%			

			Heat Exchangers			
			Double Pipe	Shell & Tube	Plate	Air-to-Liquid
Cost		30.00%	low design cost	varies per fluid	low capital cost / normal most econ.	low capital cost
Efficiency		25.00%	low eff. compared to others	lower thermal eff. (< double pipe)	high heat transfer coefficient (u)	high eff. other than small pressure drop
Capacity		25.00%				
	Temperature		max allowed pressure 300 bar	max allowed pressure <6000 psi	max allowed pressure < 1 Mpa	< capacity than air-air intercooler
	Pressure		max allowed temp 100-600 C	max allowed temp - 250-800 C	max allowed temp 150-400 C	eff ranges 60-70% max is 90%
Size		10.00%	large 0.25-200 m^2, mult. units	10-1000 m^2 per shell	1-2500 m^2	compact
EHS		10.00%	exposed pipes warm, water spills	most common, durable, adaptable	surfaces easily accessible to clean	water level needs atte., minor needs
	Maintenance		low maintenance, simple design	bad for high viscous fluids	good low viscosity, low T changes	water,antifreeze prevent corrosion
	Safety		most critical areas insulated	subject to flow-induced vibration	potential for leakage	leak in main cooler core, engine prob.
Total		100.00%				